

MIAA
NAG 1-182

Second Harmonic Generation of a cw Diode-Pumped Nd:YAG Laser using an Externally
Resonant Cavity

W. J. Kozlovsky, C. D. Nabors, and R. L. Byer

Edward L. Ginzton Laboratory

Stanford University

Stanford, California 94305

(415) 723-1718

LANGLEY
7N-36-CR
213/15
98.

The recent development of high-power laser diodes has renewed interest in diode-laser-pumped solid-state lasers. Diode-pumped lasers offer improved reliability, efficiency, and frequency stability¹ compared to lamp pumped lasers. Second harmonic generation (SHG) of these infrared laser sources is necessary for many applications. However, the lower power available from diode pumped lasers makes efficient frequency doubling more challenging than for high power lamp-pumped lasers.

One demonstrated method for efficient SHG of diode pumped solid state lasers is intracavity frequency doubling.² The nonlinear crystal is placed inside the laser resonator to take advantage of the high circulating intensity to efficiently produce second harmonic output. In these linear laser resonators, however, spatial hole burning usually allows several axial modes to oscillate. Since the losses of these axial modes are coupled through sum frequency generation in the doubling crystal, the resulting output at the second harmonic is strongly amplitude modulated³.

An alternative approach is resonant external cavity SHG⁴. In this method, the nonlinear medium is placed in an external resonator designed to enhance either the fundamental field, the second harmonic field, or both. These resonantly enhanced fields efficiently generate second harmonic power without the amplitude instabilities seen in intracavity frequency doubling. An additional advantage of external cavity SHG is that the

(NASA-CR-185085) SECOND HARMONIC GENERATION
OF A CW DIODE-PUMPED Nd:YAG LASER USING AN
EXTERNALLY RESONANT CAVITY (Stanford Univ.)

N89-71411

9 p

Unclas
00/36 0213115

laser oscillator and the external harmonic resonator can be independently optimized. This is especially important in low gain or quasi-three-level laser systems.⁵ Independent optimization also allows the design of a single axial mode laser source, insuring that the output of the external doubler is also in a single axial mode.

External cavity resonant SHG requires the coincidence of the laser and external resonator frequencies. Thus a single-axial-mode, frequency stable laser oscillator⁶ is important. Diode-pumped, monolithic, nonplanar-ring Nd:YAG lasers^{7,8} are ideal laser sources for external resonant SHG due to their single-mode, frequency-stable output power and their good resistance to feedback.

The nonplanar ring oscillator used for these experiments has been described elsewhere by Kane, *et al*⁸. It operated TEM₀₀ and in a single axial mode with a linewidth of less than 10 kHz, with a drift of less than 1 MHz per minute. It produced 15 mW of cw output power when pumped by a 120 mW diode laser source.

MgO:LiNbO₃ was chosen for the external doubler because of its low scatter and absorption loss at 1.06 μm ⁹ and its large nonlinear and electro-optic coefficients. Both ends of a 4 x 4 x 25 mm crystal of MgO:LiNbO₃ were polished with 20 mm radius of curvatures, and then coated to be 99.7% reflecting at 1.06 μm . This monolithic cavity design provided stability of the resonant frequency and also minimized cavity losses which is essential for large field enhancements in the external resonator. The cavity geometry with an n_o of 2.23 yield a cavity beam waist of 38 μm and an axial mode spacing of 2.7 GHz. The MgO:LiNbO₃ cavity resonant frequency was tuned by applying a voltage across the crystal y-axis, using the r_{22} electro-optic coefficient to change n_o and thereby the optical path length. One free spectral range was scanned with 1040 Volts.

Figure 1 shows a schematic of the experimental setup. For the doubling experiments, the oven containing the monolithic MgO:LiNbO₃ crystal resonator was heated to the noncritical 90° phasematching temperature of 107 C. Spatial mode matching into the doubling cavity was accomplished with a 10 cm focal length lens and proper adjustment to

the position and orientation of the harmonic crystal. This was the only mechanical adjustment needed since the monolithic design insured alignment of the MgO:LiNbO_3 resonator itself. A Faraday isolator was placed between the laser and the doubler to collect the fundamental radiation back-reflected from the doubling crystal, which was a minimum at resonance. On resonance, the high circulating intensity of the fundamental in the doubling crystal efficiently generated second harmonic. Since the external doubler was a standing wave resonator, the second harmonic was generated in both directions. The use of two dichroic mirrors allowed both of the harmonic output beams and the transmitted fundamental beam to be measured.

Figure 2 shows the total generated second harmonic power as a function of incident fundamental power. A commercial scanning confocal interferometer was used to verify that the second harmonic output was single axial mode. At 15 mW of input power, 2 mW of second harmonic power was generated, yielding a conversion efficiency of 13%. The bias voltage necessary to maintain resonance drifted slowly, probably due to photoconductivity screening of the voltage applied across the crystal.¹⁰ Resonance was maintained by a servo loop based on the detection of the reflected fundamental, with a small dither signal applied to the feedback voltage on the doubler. With the cavity locked, the output at the second harmonic had amplitude fluctuations of less than 5%, largely due to technical noise in the servo-loop.

With the crystal at room temperature, the harmonic generation process was not phasematched so that no doubling occurred. The crystal resonator then operated as a high finesse interferometer. The finesse was measured to be greater than 450, indicating total losses in the resonator were less than 1.4%. Coating transmittance accounted for 0.6% of this loss, indicating that all other losses were less than 0.8% in a round trip.

The output of the doubler may be calculated using the external resonator SHG theory of Askin, Boyd, and Dziedzic (ABD)⁴. Because scattering and absorption losses in the crystal are so low, depletion of the resonated fundamental caused by SHG must be

considered. This factor is not considered in the theory of ABD, but is easily accounted for by an additional loss term that is proportional to the circulating intensity. Let $\eta_{\text{SHG}} = \gamma_{\text{SHG}} P_c$, where η_{SHG} is the conversion efficiency of the resonated fundamental to the second harmonic power and P_c is the circulating intensity of the fundamental in the doubling cavity. The proportionality factor γ_{SHG} can be derived using the formalism of Boyd and Kleinman for a focussed Gaussian beam.¹¹ Then $t_{\text{SHG}} = (1 - \gamma_{\text{SHG}} P_c)$ is the fraction of resonated fundamental not converted in a single pass of doubling. Since second harmonic is generated in both directions, the ABD cavity reflectance parameter r_m becomes

$$r_m = t^2 t_{\text{SHG}}^2 r_2 \quad (1)$$

where, following ABD conventions, t is the single pass power transmittance of the crystal, t_1 is the input mirror power transmittance, and r_2 is the back mirror power reflectance. On resonance then,

$$P_c = \frac{t_1}{(1 - \sqrt{r_1 r_m})^2} \quad (2)$$

and the total output at the second harmonic is

$$P_2 = 2 \gamma_{\text{SHG}} P_c^2 \quad (3)$$

For our crystal, with $d_{\text{eff}} = 6.7 \times 10^{-12}$ m/V and effective phasematching length of only 1.5 cm,⁹ $\gamma_{\text{SHG}} = 0.0025$ per Watt. Figure 2 shows the numerical solution to the above equations plotted as a curve along with the experimental data points. It is interesting to note that the 13% conversion from input fundamental to output second harmonic power corresponds to an internal conversion efficiency (or effective loss to the circulating intensity) of only 0.3%, and a circulating intensity of 620 mW.

The circulating intensity can also be determined by measuring the fundamental

power transmitted through mirror r_2 . Figure 3 shows the transmitted fundamental power versus incident power with and without doubling. The line is the theory and the dots are the data. The excellent agreement between theory and data indicates that all losses of the resonator, including doubling, are properly determined. The lower circulating intensity while phasematched corresponds to a reduction in the Q of the cavity due to doubling, and also to the decrease of fundamental power coupled into the resonator due to the changing reflectance parameter. During second harmonic generation, the measured fundamental power throughput and the fundamental power reflected from the resonator totaled 8 mW of the 15 mW incident power.

As stated in ABD, it is possible to perfectly couple into the external resonator, and not reflect any of the incident fundamental power (i.e. impedance match) by choosing the input mirror reflectance r_1 to equal the reflectance parameter r_m . Therefore a simple change of mirror reflectances could resonate all of the incident fundamental power, so that the conversion efficiency would approach 40% at 15 mW of input power. The performance could also be improved by replacing the standing wave resonator with a monolithic ring resonator. Such a device would provide single direction second harmonic output power and would not retroreflect the input beam into the laser resonator, thus eliminating the need for an isolator.

One possible use for the single frequency second harmonic power generated by the external resonant doubler would be to frequency stabilize the diode pumped solid-state laser by locking to a sub-Doppler absorption feature of $^{127}\text{I}_2$.¹² By adjusting the laser temperature, we were able to tune the doubler output across a Doppler-broadened line in an I_2 cell and observe bright fluorescence, indicating the possibility for a saturation spectroscopy stabilization experiment.

In conclusion, we have demonstrated 13% total second harmonic conversion efficiency from a CW input of 15 mW at $1.064\text{ }\mu\text{m}$. The measured finesse of the monolithic MgO:LiNbO_3 doubling cavity was greater than 450, indicating total resonator

losses of less than 1.4 %. The doubling cavity resonance was electro-optically locked to the laser frequency by maintaining a minimum in the reflected fundamental power. The observed high conversion efficiency from a low power CW input and the single-axial mode, frequency stable output demonstrated the advantages of externally resonant harmonic generation.

This research was supported by ARO and NASA. W.J. Kozlovsky and C.D. Nabors gratefully acknowledge support of the Fannie and John Hertz Foundation. We thank Crystal Technology for providing the MgO:LiNbO_3 .

References:

- ¹ B. Zhou, T. J. Kane, G. J. Dixon, and R. L. Byer, *Opt. Lett.* **10**, 62 (1985).
- ² T. Y. Fan, G. J. Dixon, and R. L. Byer, *Opt. Lett.* **11**, 204 (1986).
- ³ T. Baer, *J. Opt. Soc. Am. B* **3**, 1175 (1986).
- ⁴ A. Askin, G. D. Boyd, and J. M Dziedzic, *IEEE J. Quantum Electron.* **QE-2**, 109 (1966).
- ⁵ T.Y. Fan and R. L. Byer, *IEEE J. Quantum Electron.*, **QE-23**, 605 (1987).
- ⁶ Thomas J. Kane and R. L. Byer, *Opt. Lett.* **10**, 65 (1985).
- ⁷ W. R. Trutna, Jr., D. K. Donald, and Moshe Nazarathy, *Opt. Lett.* **12**, 248 (1987).
- ⁸ Thomas J. Kane, Alan C. Nilsson, and Robert L. Byer, *Opt. Lett.* **12**, 175 (1987).
- ⁹ J. L. Nightingale, W. J. Silva, G. E. Reade, A. Rybicki, W. J. Kozlovsky, and R. L. Byer, in *Proceedings of SPIE*, Vol. 681, *Lasers and Nonlinear Optical Materials* (Society of Photo-Optical Instrumentation Engineers, Bellingham, 1987), p. 20.
- ¹⁰ A. Cordova-Plaza, M. J. F. Digonnet, and H. J. Shaw, *IEEE J. Quantum Electron.*, **QE-23**, 262 (1987).
- ¹¹ G. D. Boyd and D. A. Klienman, *J. Appl. Phys.* **39**, 3597 (1968).
- ¹² Peter Esherick and Adelbert Owyong, *J. Opt. Soc. Am. B* **4**, 41 (1987).

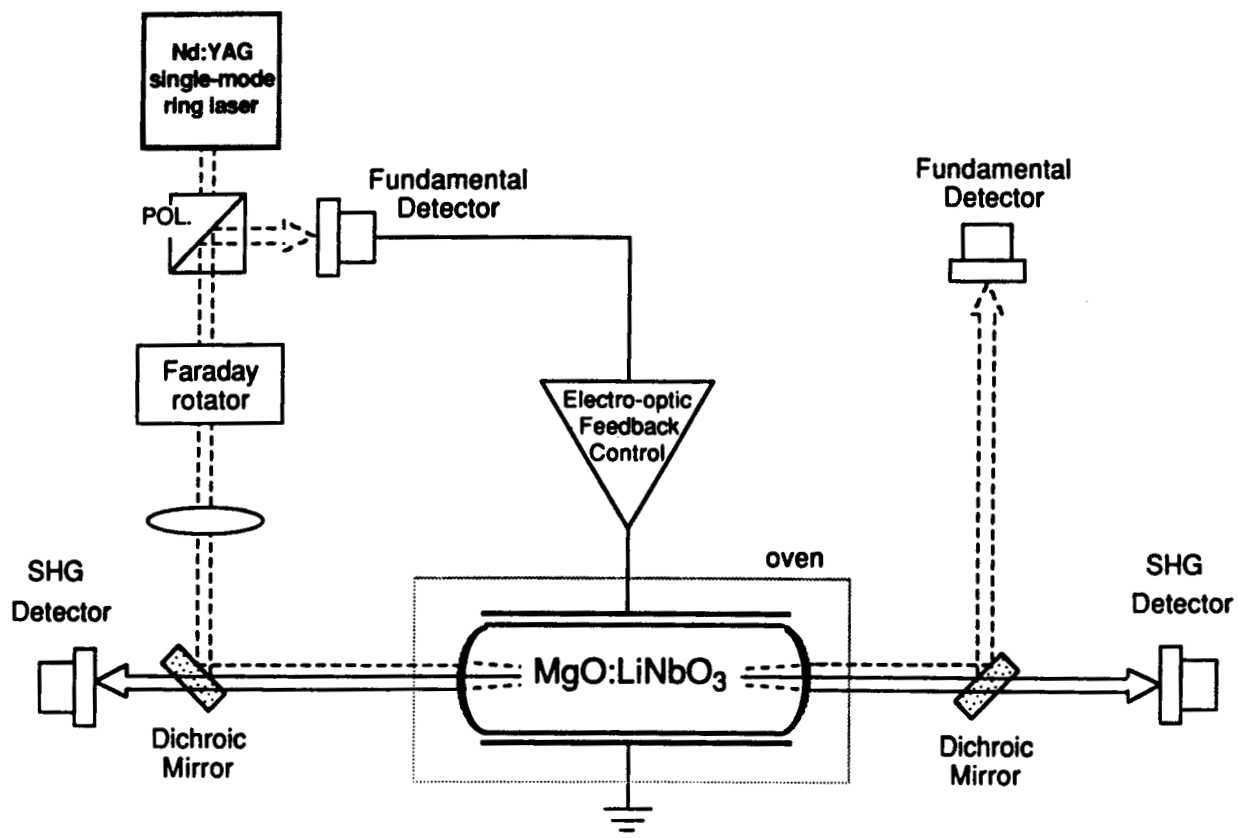


Figure 1. Experimental Set-up. The two dichroic mirrors allow the power in both second harmonic outputs to be measured, as well as the transmitted fundamental power. The Faraday isolator allows the fundamental power back-reflected from the doubling cavity to be detected and therefore used for feedback in optimizing resonance.

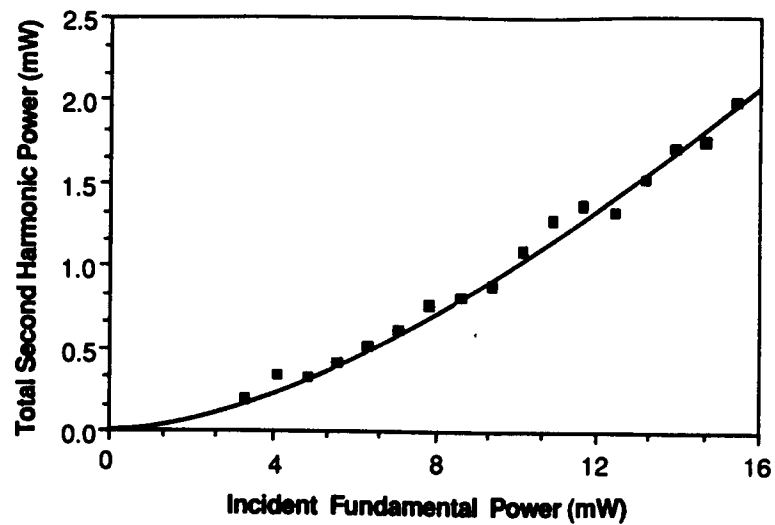


Figure 2. Total second harmonic power vs. incident power at the fundamental. The points are experimental data and the line is theory. The non-parabolic output is expected theoretically, since the coupling efficiency into the resonator changes with increasing second harmonic conversion.

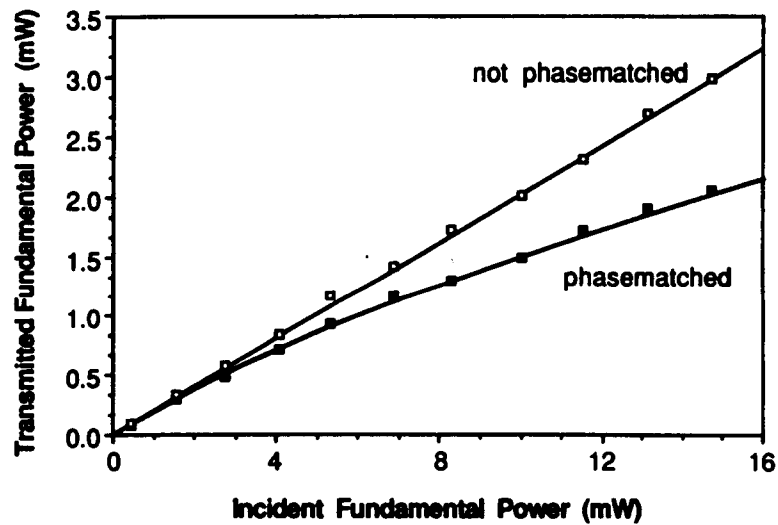


Figure 3. Transmitted fundamental power as a function of incident power at the fundamental. The transmitted fundamental is directly proportional to the circulating power in the resonant doubler and can be used for comparison with theory.